

Study of the influence of the design of the turning tool on the removal of thermal energy from the cutting zone

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Abstract. In this work, we performed a study and developed the design of through-cutters that provide accelerated heat removal from the cutting zone with external turning. Using SolidWorks Simulation engineering analysis and SolidWorks Flow Simulation gas-hydrodynamic analysis modules as a research tool, we created a basic 3D model of a precast cutter and carried out a thermal analysis of the transition process to determine the distribution of temperature fields in the body of the cutter throughout time during the cutting process. After that, we made changes to the design of the cutter, specifically, created a cavity in the holder body in which the copper core was placed. We then re-performed the studies described above, which showed that when using a copper core, the temperature in the cutting zone decreases by 246 °C within 15 minutes from the start of the work. To obtain a greater effect, we added a hole in the copper core and used air cooling, which allowed reducing the temperature in the cutting zone by 313 °C.

1. Introduction

It is well known that when cutting metals, more than 99 % of mechanical energy is converted into thermal energy, most of which is transferred to the part, cutter and shavings. Numerous experimental studies by various groups of scientists [1–3] demonstrated that the largest amount of heat – from 60 to 85 % – goes into shavings; 25–35 % goes into the part, 3–15 % into the tool and 1–2 % into the environment. Despite the fact that the percentage of thermal energy transferred to the cutter is small, the absolute value of the temperature at the tool pads and in the cutting wedge itself is significant, and with increase in cutting speed it can reach 1000 °C and higher [4].

High temperatures negatively affect tool life and can lead to damage and premature wear of carbide inserts, e.g. growths on the cutting edge, deformation of the cutting edge, chipping of the tool and the insert, etc. [5, 6].

Premature wear of a replaceable carbide plate affects the accuracy of machining parts and workpieces, and may adversely impact the equipment itself.

For effective cutting, it is necessary to maintain the temperature within acceptable limits, reducing heat generation and removing heat from the cutting zone as much as possible.

There are various ways to reduce heat during cutting.

Firstly, the choice of the cutting mode is of great importance. It is well known that more heat is generated as cutting speed increases. However, at the same time, heat removal through shavings is increased because more shavings are generated per unit of time. An increase in feed is also favorable for heat dissipation due to the formation of thicker shavings [7, 8].



Further, cutting fluid is widely used to remove heat from the cutting zone. However, the use of coolant is associated with significant costs, which in most cases make up to 2–8 % of production costs, i.e. are comparable with the cost of the tool itself [9]. These costs are driven by the need to acquire and dispose of the coolant. In addition, the high temperature in the cutting zone causes coolant to evaporate, resulting in temperature spikes. The combination of temperature spikes and mechanical pressure leads to damage to the cutting edge, whereas perpendicular cracks form along the working surface, while particles of the material can fall off, causing chipping. In terms of environmental friendliness, coolant also has major disadvantages. Since the critical temperature of the coolant components (130–200 °C) is much lower than the average temperature in the cutting zone, they are prone to thermal destruction during cutting. As a result of this, harmful substances enter the air of the working zone, and, when their normative content in the air is exceeded, have a negative effect on the health of workers, causing occupational diseases [10]. Waste coolant discharged into the wastewater is a major pollutant of water and soil. Metal shavings left over from machining and contaminated with coolant are not always cleaned and are also a source of pollution and contamination [11]. Therefore, additional investments are required to neutralize production waste.

At the current technological level, it is not possible to completely abandon the coolant. For example, in boring, drilling and cutting operations, when it is difficult to remove shavings or when the machined surfaces must be measured while being cut, abundant cooling is required.

In modern metal processing, the problem of heat removal ought to be solved not only by supplying coolant to the cutting zone, but also by creating designs of cutting tools that provide accelerated heat removal from the cutting zone [12–14].

The work we currently present is devoted to the study of the influence of the thermal conductivity of the cutter on the heat removal from the cutting zone with external turning.

Increasing the thermal conductivity of the cutter is critical to prolonging the cutter's service life. Higher thermal conductivity improves the conditions for heat removal from the cutting zone, which reduces the cutting temperature and increases the wear resistance of the tool.

2. Research methodology

Our solution to this problem is based on modeling the heat transfer process during cutting in the SolidWorks Simulation system. Thermal analysis in this system includes the calculation of both stationary and non-stationary (transient) thermal process. Transient research models the distribution of thermal energy over time. The initial data in this case is the thermal load applied to the body.

The research algorithm is as follows:

1. To create a model of the basic design of the cutter, this will be a prototype for comparison with subsequent modernized designs.
2. Set the application area and the value of thermal load, initial and boundary conditions.
3. Perform analysis of heat transfer in the model of the basic design of the cutter and obtain graphs of the dependence of the distribution of thermal energy in time.
4. Create models of modernized designs and obtain comparison graphs following the methodology described above.
5. Based on a comparison of the results, draw conclusions about the advisability of upgrading the design of the cutter.

2.1. Study of the heat sink of the base design

As a basic design, we created a precast cutter with a cross section of a holder 32×35mm made of steel 40X, angles $\gamma = -6^\circ$, $\varphi = 45^\circ$, $\varphi_1 = 6^\circ$, $\varepsilon = 90^\circ$, $\alpha = 6^\circ$, $\alpha_1 = 6^\circ$, $\lambda = -6^\circ$. Tungsten carbide plate – SNMG 190616, the method of fastening the plate to the holder – clamp the lever above the hole (Figure 1).

The thermal study of the cutter in SolidWorks Simulation was carried out taking into account the time dependence in the range of 15 min (900 sec) – the time corresponding to the resistance period of

the replaceable plate, with a time increment of 1 sec., i.e. the heat transfer process was seen as non-stationary.

For the analysis, we determined the areas impacted by the forces that arise in the cutting process and cause a thermal load on the cutter. A heat load was applied to these areas in the form of a heat flux with a power of 17 W for a given time range. For simplicity, it was assumed that the convective heat transfer of the cutter with the surrounding air occurs only at its rear end, since the side surfaces of the holder are closed by a tool holder in which the tool is fixed. Coefficient of convective heat transfer 25 W / m² °K, ambient temperature 300 °K, initial cutter temperature 20 °C.

In the course of the study, we monitored the following parameters:

- temperature distribution along the length of the tool holder 900 seconds after application of the load;
- the change in the maximum temperature of the cutter over a given time range.

The result of the thermal calculation of the basic design of the cutter is shown in Figure 1.

The figure shows that after 900 seconds the maximum temperature reached 1035 °C and occurred at the top of the cutting edge. The rest of the interchangeable plate warmed up to ~ 300–400 °C.

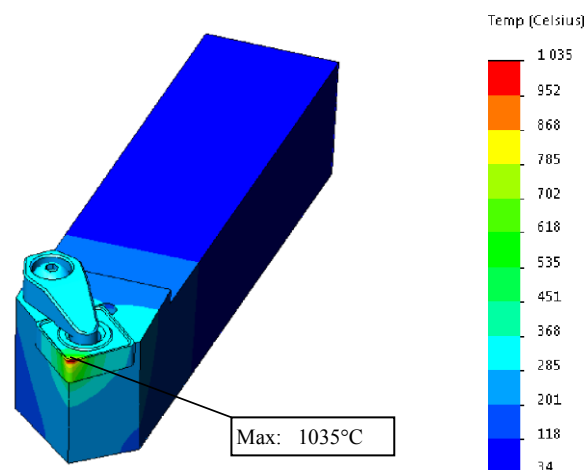


Figure 1. Temperature distribution along the length of the holder in the model of the basic design of the cutter after 900 seconds from the moment of loading.

2.2. Development of cutter designs with accelerated heat removal from the cutting zone

To study the impact of the design of the cutter on the rate of removal of thermal energy from the cutting zone, we developed several constructive variants of the initial cutter, as presented in Figure 2.

In the embodiment with a copper core shown in Figure 2 (a), a hole was made under the cutting insert in the tool holder connecting to the longitudinal hole, and the resulting cavity was filled with copper.

Figure 2 (b) shows a model of a cutter with a longitudinal hole made in a copper core; the thickness of the copper layer in the tool holder was 4 mm.

Further modernization of the cutter design, which allows increasing the heat sink, was aimed at the use of forced air convection. For this purpose, we mounted a cover on the thread on the rear end of the copper-coated cutter. A thin long tube with a diameter of 5 mm was attached to this cover on the side of the cutter, a fitting for supplying compressed air was provided on the outside, and apertures for the exit of heated air were made along the perimeter of the cover (Figure 2 (c)).

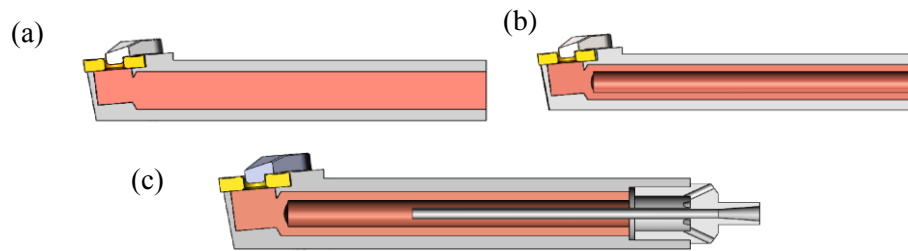


Figure 2. Design options of the initial cutter (in the context):
(a) – with a copper core; (b) – with a copper coating; (c) – with forced air convection.

2.3. The study of heat sink in the cutters designed by the Authors

Thermal analysis of the cutter models shown in Figure 2 (a) and 2 (b) was performed in SolidWorks Simulation according to the same scenario as the analysis of the basic design model described earlier. The same thermal loads were applied, and the same initial and boundary conditions and the areas impacted by the forces arising in the cutting process and causing a thermal load on the cutter were set.

The results of the thermal calculation of these incisors are presented in Figure 3.

For the cutter with the copper core of the heat flux, the maximum temperature after 900 seconds of the impact was 789°C (Figure 3 (a)). This is 246 degrees lower than in the cutter of the basic design. The heat dissipation of the copper-coated cutter (Figure 3 (b)) did not increase compared to the copper core cutter, but instead decreased, albeit slightly, by 9 degrees. This result is predictable, but the latter design option allows the use of forced air convection to increase the heat sink even further.

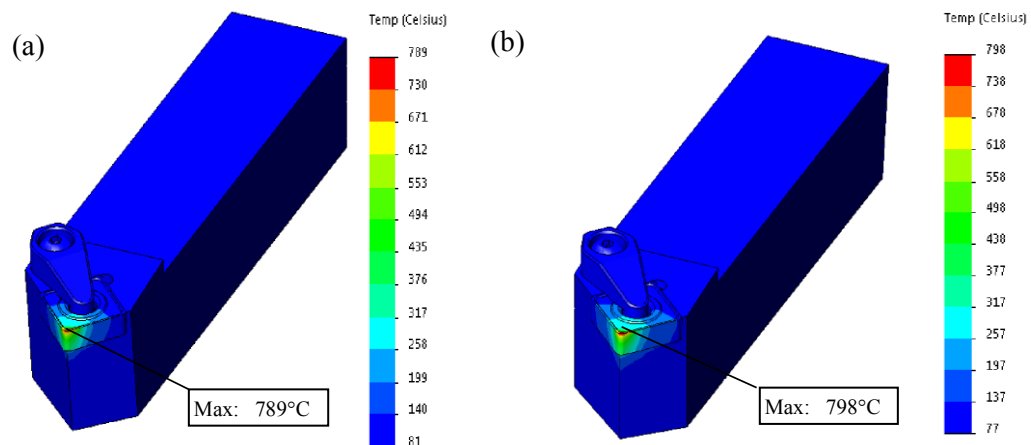


Figure 3. Temperature distribution along the length of the holder after 900 seconds from the moment of application of the heat load: (a) – in the model of the cutter with a copper core; (b) – in the model of a copper-coated cutter.

2.4. The study of heat sink cutter with forced air convection

Analysis of the design of the cutter that uses stream of compressed air to cool the copper channel was performed using the SolidWorks Flow Simulation computing tool, designed to simulate fluid and gas flows. Using this application, we calculated the trajectory of the air when it was supplied through the nozzle under a pressure of 0.6 MPa. Calculation data from SolidWorks Flow Simulation were transferred to thermal analysis, the results of which are presented in Figure 4.

According to the diagram presented in Figure 4, the maximum temperature of the cutter was 721 °C. Compared with the base case, the temperature decreased by 314 degrees.

2.5. The study of changes in the maximum temperature of the incisors during the cutting process

For each of the studied incisors, we measured and recorded the temperature at the tip of the incisor, i.e. the point at which the maximum temperature was observed after 900 sec from the moment of application of the heat load, in the interval of 900 sec with a time increment of 1 sec. Based on the results of the study, we plotted the change in the maximum temperature of the cutter over a given time range (Figure 5).

As demonstrated in the graphs presented, the temperature in the region of the cutting edge increases significantly during the first 1-3 seconds, and changes less intensively in the following 897 seconds. These results are consistent with numerous experimental studies described in the literature. [1–3, 7]

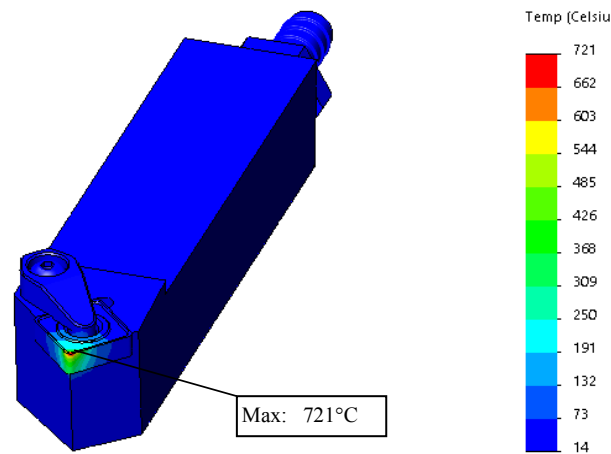


Figure 4. Temperature distribution along the length of the holder in the cutter model with forced air convection after 900 seconds from the moment of application of the heat load.

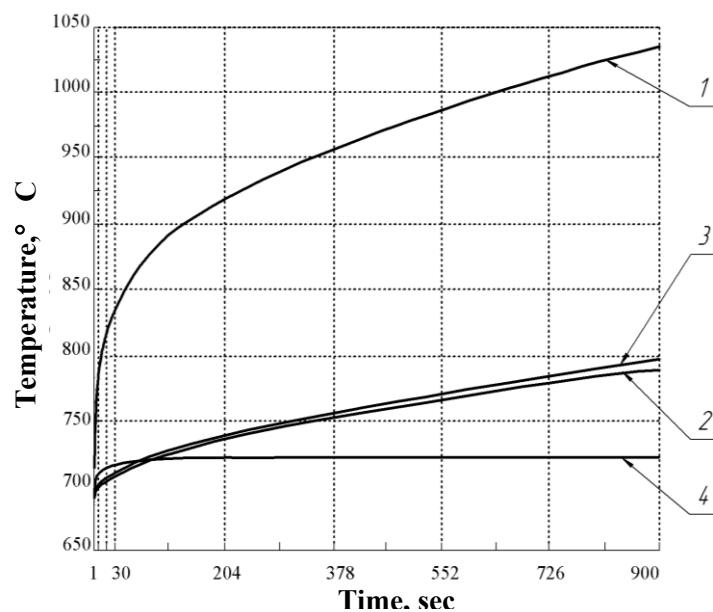


Figure 5. Graphs of changes in the maximum temperature of the incisors during the cutting process: 1 – model of the basic design; 2 – model with a copper core; 3 – model with a copper coating; 4 – air-cooled model.

3. Conclusion

Our study demonstrated that the design changes made to the basic version of the turning tool are generally beneficial. However, they are not all the same. A cutter with a copper core is quite rational and simple in terms of its heat sink performance. It is almost twice as effective as the base cutter; however, the use of a copper core makes it significantly more expensive. The cutter with an internal copper coating is less expensive than the copper core cutter and provides almost equal heat dissipation from the top of the cutter; however, its rigidity will be less. The air-cooled cutter with copper inner coating provides the greatest temperature reduction compared to the base cutter. According to preliminary estimates, its manufacturing cost will be one and a half times higher than that of the base version. At the same time, it appears its rigidity will be the same.

Given the above, we believe that a cutter with an internal copper core can be recommended for use in ordinary turning of billets made of structural steels, when the task of increasing the heat removal from the top of the cutter is quite relevant, but not critical. An internal copper-coated air-cooled cutter is probably the most efficient use for high speed finishing. A copper-coated cutter without air cooling can be used in medium-speed machining, when the cutting speed is relatively high, but does not reach very high values characteristic of high-speed turning.

This study is only a pilot. In the future, we plan to refine and expand it, which will make it possible to discuss the specific areas of application of the proposed modifications in greater detail.

References

- [1] Reznikov A N and Reznikov L A 1990 *Thermal processes in technological systems: textbook* (Moscow: Mechanical Engineering) p 288 [In Russian]
- [2] Abramov F N, Kovalenko V V, Lyubimov V E and others 1983 *Handbook of metal cutting* (Kiev: Technique) p 239 [In Russian]
- [3] Bobrov V F 1975 *Fundamentals of the theory of metal cutting* (Moscow: Engineering) p 344 [In Russian]
- [4] Budadin O N, Vavilov V P and Abramova E V 2013 *Thermal control* (Moscow: Publishing house 'Spectrum') p 176 [In Russian]
- [5] Serebrennikova A G and Panova E A 2016 *Technological support for the quality of engineering products* (Stary Oskol: TNT) p 392 [In Russian]
- [6] Vasin S A, Vereshchak A S and Kushner V S 2001 *Cutting materials: Thermomechanical approach to the system of relationships in cutting* (Moscow: Ed MSTU named after N E Bauman) p 448 [In Russian]
- [7] Stahl Jan Eric et al 2012 *Metal Cutting: Theories and Models* (Lund: Lund Inicersity Press) p 580
- [8] Ali Riza, Motorcu 2010 The Optimization of Machining Parameters Using the Tguchi Metod Ali Riza Motorcu *Journal of Mechanical Engineering* vol **56** (6) pp 391–401
- [9] Voskoboev V F 2008 *Reliability of technical systems and technological risk* (Moscow: LLC Publishing House Alliance) p 200 [In Russian]
- [10] Artemyeva M S 2015 The effect of thermal phenomena during the processing of metals by cutting on cutting lubricants *Life Safety* no **6** (174) pp 9–14
- [11] Kamenskaya A A, Kovalova R I and Labetskiy V M 1992 *The environmental impact of metal processing by cutting of machine-building enterprises on the environment and ways to reduce damage: Analit. review GPNTB SB RAS Alt Polytechnic in-t* (Novosibirsk: SPSL SB RAS) p 102 [In Russian]
- [12] Sanchez L E A, Scalón V L, Abreu G G C and Cleaner Machining 2011 Through a Toolholder with Internal Cooling *Proc. of third int. workshop on advances in cleaner production* (São Paulo, Brazil) pp 18–20
- [13] Vicentin G C, Sanchez L E A, Scalón V L and Abreu G G C 2011 A sustainable alternative for cooling the machining processes using a refrigerant fluid in recirculation inside the toolholder *Clean Technologies and Environmental Policy* vol **13** Issue **6** pp 831–40
- [14] Liberman Y L and Rastyagaeva E S Metalworking tools with cooling (patent 196895 RU)